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International Earth Science Constellation

Mission Operations Working Group

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Earth Observation System Covariance Realism Updates

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Agenda

- CARA Synthesized vs. FDS Tuned Covariances
- EOS Covariance Realism QA and Tuning Flowchart
- Covariance QA Cadence
- Covariance QA Automation
- Automation Results to Date
- Covariance Propagation Implementation through Maneuvers
- Conclusion

Purpose

- Aqua and Aura Owner/Operator covariances are being used in operations to compute P_C :
 - Software has been delivering tuned covariance since 14 Jun 2016.
 - Software ensures both covariances are tuned for periods devoid of persistently high and extreme solar activity as well as post maneuver propagation errors.
- Describe and demonstrate the operation of the following items:
 1. Automation of covariance Quality Assurance (QA) ([monitor](#)) and Outlier Identification.
 2. Method to periodically tune ([maintain](#)) the covariance.
 3. Method to inflate covariance at burn start based on historical maneuver execution error.
- Describe automation results to date:
 - What Realism Pass Percentages have we encountered and what outliers have been identified since the software's release?

CARA Synthesized Covariance

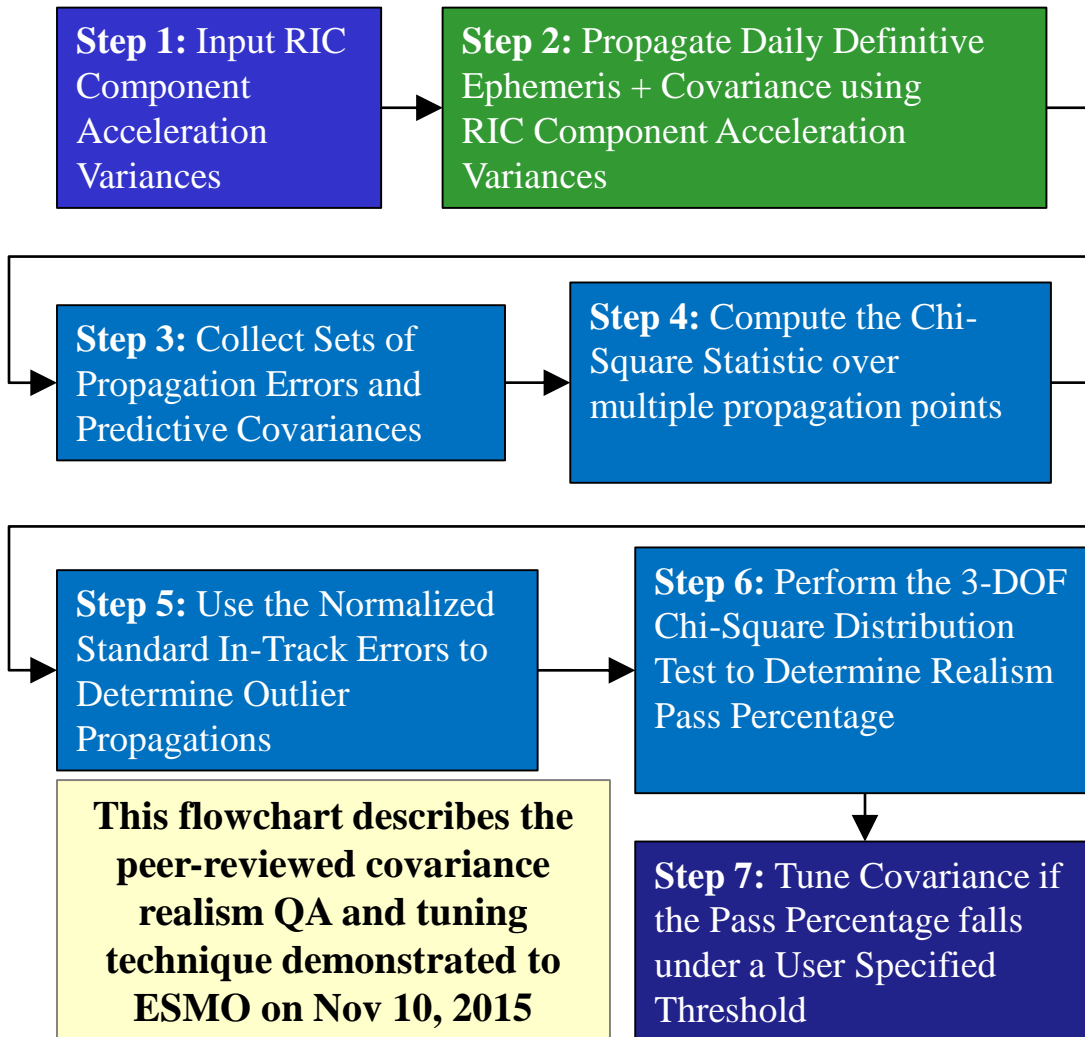
- Prior to Jun 14, 2016, both Aqua and Aura used synthesized covariances that were averaged JSpOC covariances over fixed quarterly timespans:
 - These covariances do not account for historical maneuver execution error and are not tested for realism.
- The synthesized covariance is binned to durations between OCM creation time and the TCA of a conjunction.
- O/O covariances are tuned to 3 days (timeframe at which ESMO starts risk mitigation maneuver planning).
- A FDS analyst runs a script that automatically checks covariances for realism using a rolling 3-month period:
 - The script notifies the analyst when realism percentages fall under a user-specified threshold (recommendation provided later).

- **EOS FDS is tuning O/O covariances to realistic distributions of O/O propagation errors (with proper outlier identification).**
- **EOS FDS is adding realistic maneuver execution error to the O/O covariance for predicted post-maneuver conjunctions.**
- **Therefore, the EOS FDS O/O covariances are the superior statistical representation of propagation errors for Pc evaluation.**

bin_start	bin_stop	covUU	covVV	covWW
0	0.25	7.478631	88.09767	6.19776
0.25	0.5	8.306914	184.8037	5.772984
0.5	0.75	9.815	355.8	5.316
0.75	1	11.38	610	5.338
1	1.25	12.06871	1270.433	6.378623
1.25	1.5	13.89	2613	6.285
1.5	1.75	16.25	4656	5.912
1.75	2	16.34434	6751.369	5.480308
2	2.25	19.92	8860	7.442
2.25	2.5	22.77458	14619.99	8.183402
2.5	2.75	27.00979	21799.89	4.73377
2.75	3	28.13	30910	4.213
3	3.25	27.23722	37346.84	9.285997
3.25	3.5	33.02879	50790.7	5.540745
3.5	3.75	39	62420	4.521
3.75	4	39.05	88040	4.518
4	4.25	41.74464	106182.8	7.008892
4.25	4.5	51.66	136900	6.351
4.5	4.75	48.73	166700	4.188
4.75	5	53.3	208900	4.905
5	5.25	56.06	254500	8.716
5.25	5.5	52.28536	294498.6	5.883996
5.5	5.75	65.19	348900	4.547
5.75	6	69.07	445600	5.553
6	6.25	67.83	473900	7.869
6.25	6.5	61.53	545200	7.919
6.5	6.75	84.04	598400	5.047
6.75	7	87.18	697000	5.753
7	7.25	81.28	766900	10.74

CARA Synthesized Covariance for Aqua; Covariance UVW
Diagonals are given in square-meters

EOS Covariance Realism QA and Tuning Flowchart



- The acceleration variances in Step 1 can only be changed via a Configuration Management Request (CMR) with ESMO Management sign off.
- Step 2 is performed as part of the nominal daily product delivery.
- Steps 3 to 6 represent the QA of the covariance and are performed via automation using FreeFlyer and MATLAB.

The frequency of automated QA (currently set to daily) could change once the frequency of tuning is established.

A single Covariance QA and Tuning SOP has been created and reviewed to aid analysts in understanding how to QA and tune the covariance for a specific propagation timespan.

Covariance QA Automation

Covariance QA Cadence

- QA of Aqua and Aura covariances is performed over a rolling 90-day timespan
- The Start Date of the First QA Ephemeris is set to 94 days prior to today's current Product DOY and the Start Date of the Last QA Ephemeris is set to 4 days prior to today's current Product DOY.
- For example, suppose the designation of the first ephemeris in the Covariance QA timespan is 'Start DOY' (= Product DOY – 94 days), then the ephemerides are tested in the following sequence:
 - Set 1 (Containing 30 Ephemerides): Start DOY, Start DOY + 3, ..., Start DOY + 87.
 - Set 2 (Containing 30 Ephemerides): Start DOY + 1, Start DOY + 4, ..., Start DOY + 88.
 - Set 3 (Containing 30 Ephemerides): Start DOY + 2, Start DOY + 5, ..., Start DOY + 89.
- Testing with a 3-day cadence is statistically required in order to isolate the affects of the 2 ½ days worth of rolling TDRS observations that go into daily FDF orbit determination runs

Ephemeris #	Set 1	Set 2	Set 3
1	2016,03,01,12,0,0	2016,03,02,12,0,0	2016,03,03,12,0,0
2	2016,03,04,12,0,0	2016,03,05,12,0,0	2016,03,06,12,0,0
3	2016,03,07,12,0,0	2016,03,08,12,0,0	2016,03,09,12,0,0
4	2016,03,10,12,0,0	2016,03,11,12,0,0	2016,03,12,12,0,0
5	2016,03,13,12,0,0	2016,03,14,12,0,0	2016,03,15,12,0,0
6	2016,03,16,12,0,0	2016,03,17,12,0,0	2016,03,18,12,0,0
7	2016,03,19,12,0,0	2016,03,20,12,0,0	2016,03,21,12,0,0
8	2016,03,22,12,0,0	2016,03,23,12,0,0	2016,03,24,12,0,0
9	2016,03,25,12,0,0	2016,03,26,12,0,0	2016,03,27,12,0,0
10	2016,03,28,12,0,0	2016,03,29,12,0,0	2016,03,30,12,0,0
11	2016,03,31,12,0,0	2016,04,01,12,0,0	2016,04,02,12,0,0
12	2016,04,03,12,0,0	2016,04,04,12,0,0	2016,04,05,12,0,0
13	2016,04,06,12,0,0	2016,04,07,12,0,0	2016,04,08,12,0,0
14	2016,04,09,12,0,0	2016,04,10,12,0,0	2016,04,11,12,0,0
15	2016,04,12,12,0,0	2016,04,13,12,0,0	2016,04,14,12,0,0
16	2016,04,15,12,0,0	2016,04,16,12,0,0	2016,04,17,12,0,0
17	2016,04,18,12,0,0	2016,04,19,12,0,0	2016,04,20,12,0,0
18	2016,04,21,12,0,0	2016,04,22,12,0,0	2016,04,23,12,0,0
19	2016,04,24,12,0,0	2016,04,25,12,0,0	2016,04,26,12,0,0
20	2016,04,27,12,0,0	2016,04,28,12,0,0	2016,04,29,12,0,0
21	2016,04,30,12,0,0	2016,05,01,12,0,0	2016,05,02,12,0,0
22	2016,05,03,12,0,0	2016,05,04,12,0,0	2016,05,05,12,0,0
23	2016,05,06,12,0,0	2016,05,07,12,0,0	2016,05,08,12,0,0
24	2016,05,09,12,0,0	2016,05,10,12,0,0	2016,05,11,12,0,0
25	2016,05,12,12,0,0	2016,05,13,12,0,0	2016,05,14,12,0,0
26	2016,05,15,12,0,0	2016,05,16,12,0,0	2016,05,17,12,0,0
27	2016,05,18,12,0,0	2016,05,19,12,0,0	2016,05,20,12,0,0
28	2016,05,21,12,0,0	2016,05,22,12,0,0	2016,05,23,12,0,0
29	2016,05,24,12,0,0	2016,05,25,12,0,0	2016,05,26,12,0,0
30	2016,05,27,12,0,0	2016,05,28,12,0,0	2016,05,29,12,0,0

Example of rolling Covariance QA Ephemeris sets for the

Covariance QA Automation

Visual Aids Presented to Analyst (1 of 3)

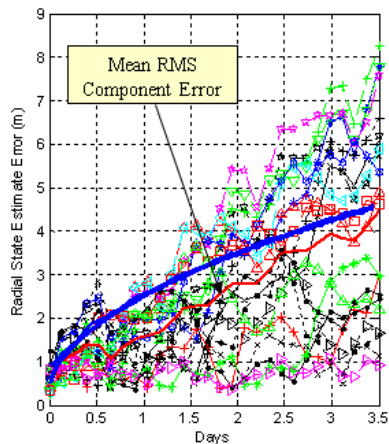


Figure 3a Mean RMS Radial Error and Predicted State Estimate Errors

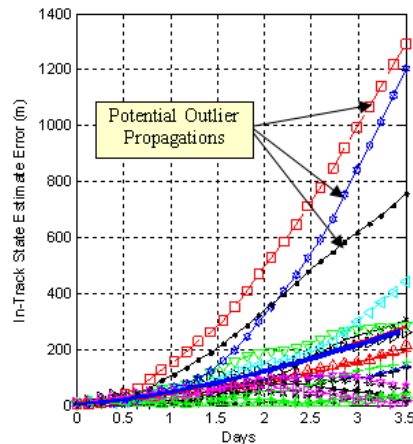


Figure 3b Mean RMS In-Track Error and Predicted State Estimate Errors

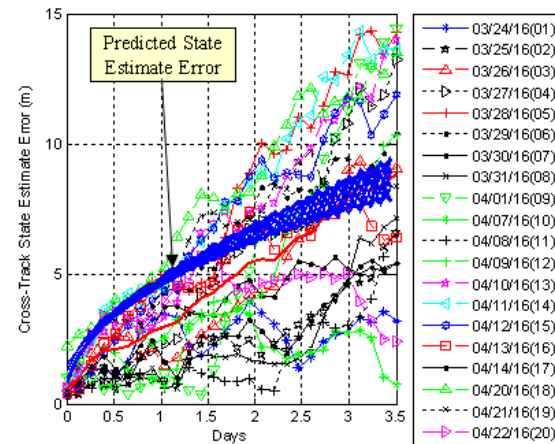


Figure 3c Mean RMS Cross-Track Errors and Predicted State Estimate Errors

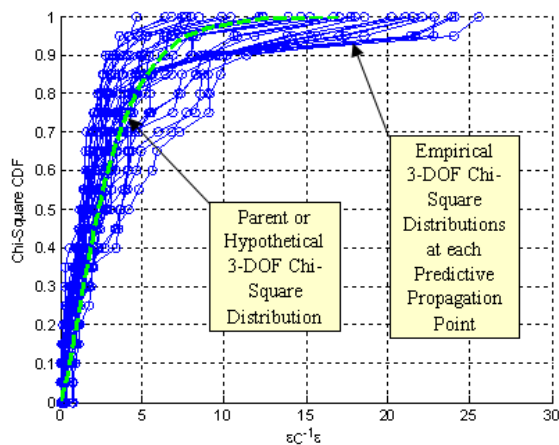


Figure 4 3-DOF Chi-Square Cumulative Distribution Function (Empirical vs. Parent)

- These are the initial plots generated by the covariance QA automation for each set of covariances it is analyzing.
- They give the analyst an idea of how far each component covariance is deviating from its mean RMS component error.
- An empirical 3-DOF Chi-Square distribution for each propagation point is assessed against its parent distribution.
- The Cramer-Von Mises EDF test is used to determine the likelihood each set of covariances represents a realistic distribution of the corresponding set of propagation errors tied to it – **a Covariance Realism “Pass Percentage” will be provided in a text file (discussed later).**

Covariance QA Automation Visual Aids Presented to Analyst (2 of 3)

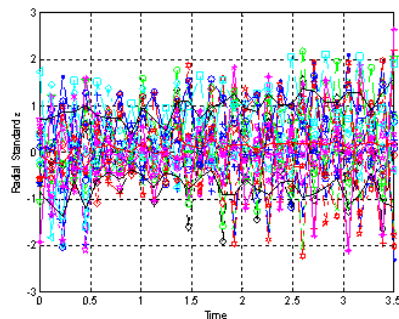


Figure 5a Standard Radial Error vs. Propagation Time

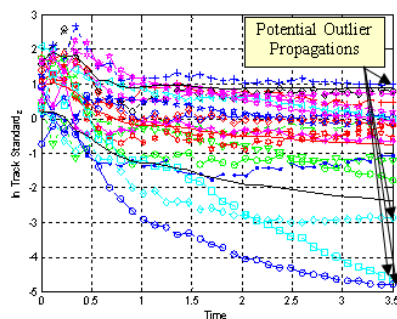


Figure 5b Standard In-Track Error vs. Propagation Time

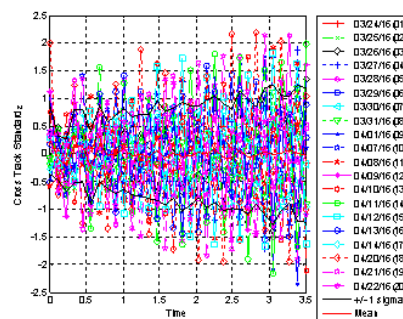


Figure 5c Standard Cross-Track Error vs. Propagation Time

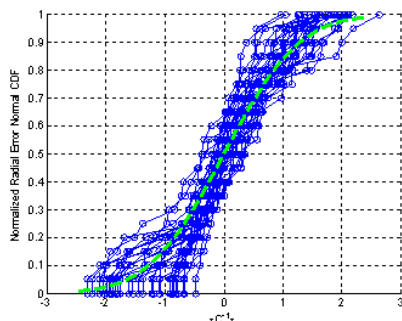


Figure 6a Standard Radial Error Cumulative Distribution Function (Empirical vs. Parent)

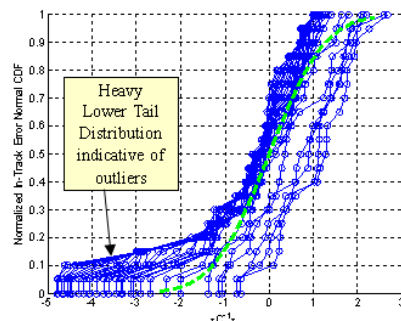


Figure 6b Standard In-Track Error Cumulative Distribution Function (Empirical vs. Parent)

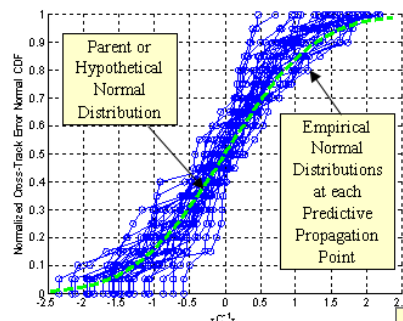


Figure 6c Standard Cross-Track Error Cumulative Distribution Function (Empirical vs. Parent)

- The next set of plots represent the Standard Component Errors
- These set of errors are tested against a normal Gaussian distribution.
- The automation uses the in-track distribution to test potential outliers.
- Any propagations outside of the $\pm 1\sigma$ bounds are tested for outlier identification

- If outliers are identified, the analyst is informed and must document a reason for dismissing the corresponding propagation.
- Naturally, the analyst checks the solar activity in the timeframe of the propagation start date to determine if there was a peak or persistently high solar activity.

Goal: Apply and track a consider parameter to the variance in the drag coefficient until outlier propagations pass the realism test for the set in which they were discovered.

Covariance QA Automation

Visual Aids Presented to Analyst (3 of 3)

Periodicity in the Radial Propagation Error is causing low levels of realism between 0.5 to 1.25 days.

The Covariance is Overestimated in this timeframe.

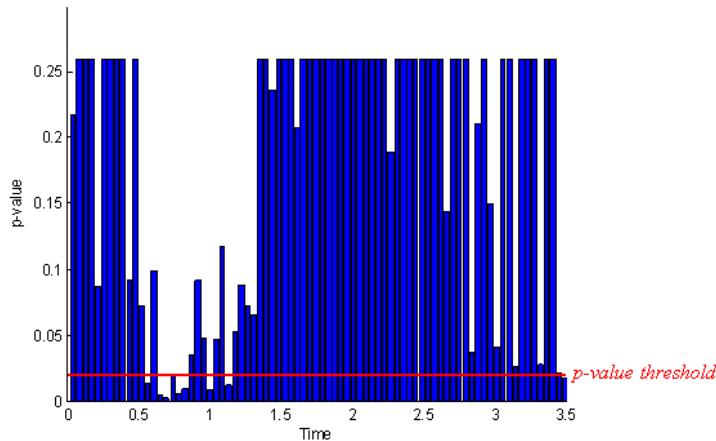


Figure 7 p-value vs. Propagation Time

3-DOF CSF Statistics:

Minutes	63	126	189	252	315	378	441	504	567
Date	0.044	0.088	0.131	0.175	0.219	0.263	0.306	0.350	0.394
24-Mar-2016	1	1.924267	3.428695	1.914728	3.970593	2.833819	1.897969	2.188777	1.231428
25-Mar-2016	2	1.488633	2.030350	3.777087	3.104311	3.139208	3.162751	1.270498	3.332144
26-Mar-2016	3	2.802741	6.215795	4.904883	6.456114	6.742696	5.203412	5.894308	3.942940
27-Mar-2016	4	2.707113	1.651023	5.821605	7.565275	2.690661	7.728362	7.391778	8.112912
28-Mar-2016	5	3.178494	3.006587	4.210462	1.568880	3.990282	3.717282	1.855421	2.795861
29-Mar-2016	6	2.300238	2.251163	1.095594	0.422951	3.384889	2.822386	2.22943	0.446098
30-Mar-2016	7	7.458491	0.960888	5.483316	3.176164	3.337632	2.457944	1.088529	2.585847
31-Mar-2016	8	1.243148	0.364064	1.209421	1.735895	1.450162	1.794027	1.275434	2.371975
01-Apr-2016	9	0.252330	0.095447	0.673278	1.023349	2.295179	1.165904	0.898745	1.298680
07-Apr-2016	10	0.408500	1.344054	0.365536	2.053457	2.035293	1.230046	0.464123	2.203104
08-Apr-2016	11	0.585188	1.371787	1.594715	0.955237	2.629396	0.820769	0.527213	0.582405
09-Apr-2016	12	2.814138	2.875505	1.627216	4.473030	2.477185	1.880055	2.989359	1.391076
10-Apr-2016	13	0.597008	2.423296	2.438999	1.582202	4.198185	3.245098	0.854633	2.323349
11-Apr-2016	14	2.230022	4.551375	2.520198	3.945883	3.183381	2.249004	2.777065	1.080868
12-Apr-2016	15	1.041139	0.200635	3.312478	3.400206	0.098994	3.197151	3.360582	3.372750
13-Apr-2016	16	0.211482	0.627784	0.512715	0.188360	1.052631	0.935510	1.281244	0.231603
14-Apr-2016	17	2.900088	2.011033	1.567180	0.873048	4.429758	4.637544	2.083363	1.782886
20-Apr-2016	18	2.498514	4.158873	5.017796	5.146978	4.635413	3.561550	5.725441	4.592125
21-Apr-2016	19	1.380735	1.064827	4.340914	6.520645	2.525371	6.810488	8.203482	7.082155
22-Apr-2016	20	4.164240	2.812117	5.017812	3.428051	3.927389	3.727476	3.656074	5.785119
Mean	2.189292	2.173305	2.870247	3.061623	3.039776	3.110637	2.800771	2.825487	2.514184
Median	2.113252	2.030691	2.479599	3.140248	3.007600	2.989769	2.136070	2.347662	1.674878
Behavior	Overized	Overized	Overized	Underized	Underized	Underized	Overized	Overized	Overized
QTrane	0.233030	0.175594	0.038495	0.041396	0.376210	0.141519	0.042978	0.054796	0.141186
QTrane	0.080974	0.031994	0.047103	0.040248	0.278029	0.088900	0.043103	0.016839	0.090771
P-value	0.137042	1.158835	0.414087	0.309186	1.877130	0.903488	0.351642	0.147207	0.747653
Test Pass/Fail	0.217940	0.260000	0.260000	0.260000	0.087189	0.260000	0.260000	0.260000	0.260000
Pass Percentage	86.75%	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS

Chi-Square Statistics

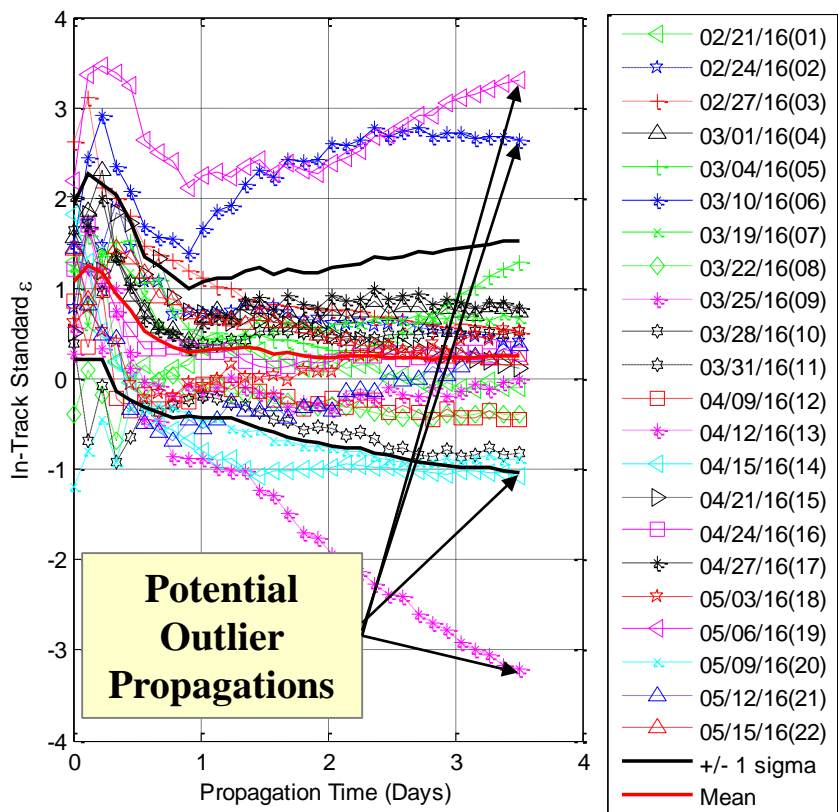
Covariance Percentage Realism over Propagation Time Span

Figure 8 Chi-Square Distribution Test Text File

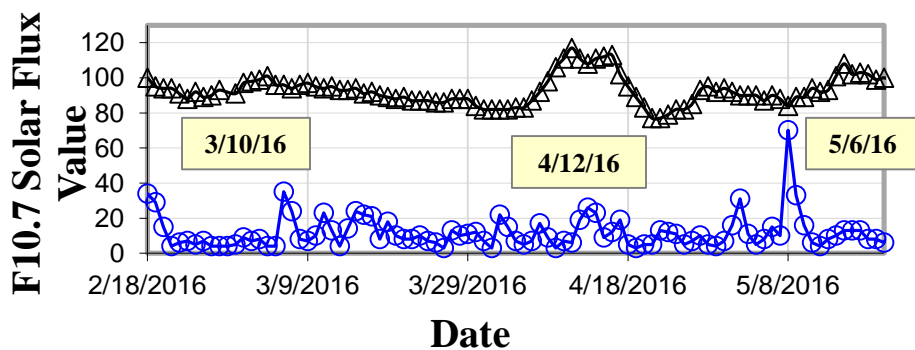
- These are the final two files the automation generates for each set of covariances it is testing.
- The p-value vs. Propagation Time chart gives the analyst information regarding where in the propagation the covariances are passing the realism testing – the analyst is able to cross-reference these propagation times with the Time of Closest Approach of a imminent conjunction.
- The Chi-Square Distribution Test Text File contains the overall Pass Percentage of each set of covariances.

Based on seasonal covariance tuning from 2014 to 2016, FDS recommended this threshold be set to 60% – a statistically commendable result.

Covariance QA Automation Outlier Identification Confirmation



- Outlier tests were performed manually to determine if the automation is correctly taking them out.
- For example, the 30-day QA test from 21 Feb 2016 to 15 May 2016 automation set determined the 10 Mar 2016, 12 Apr 2016, and 06 May 2016 propagations were outliers.
- The manual procedure performs the Rosner Outlier Test on the normalized In-Track standard errors – the test will detect outliers that are either much smaller or larger than the rest of the data and is designed to avoid the problem of masking, where an outlier close to another outlier goes undetected.
- The outliers are entered into the test in order of most to least deviant.
- The script confirms the 13th, 19th, and 6th propagations are outliers.

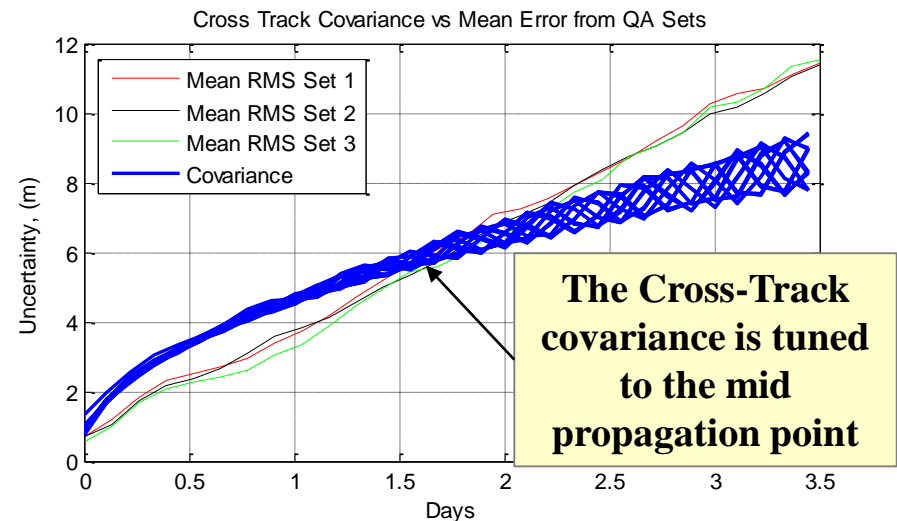
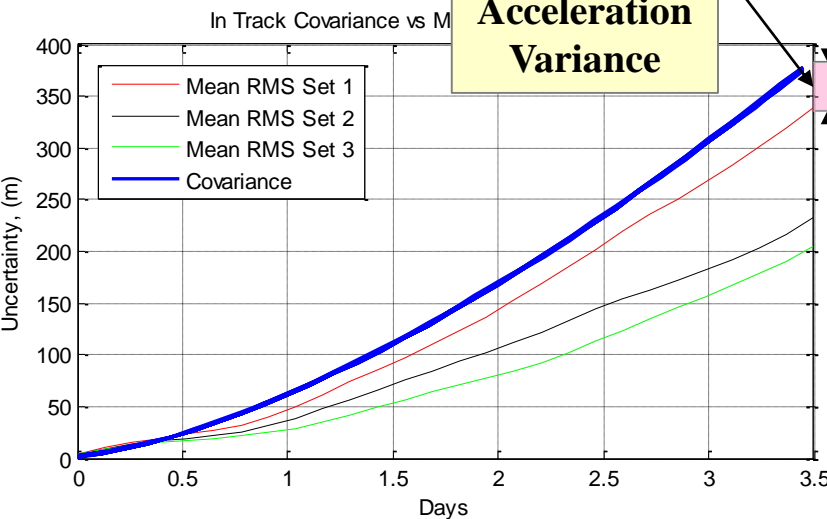
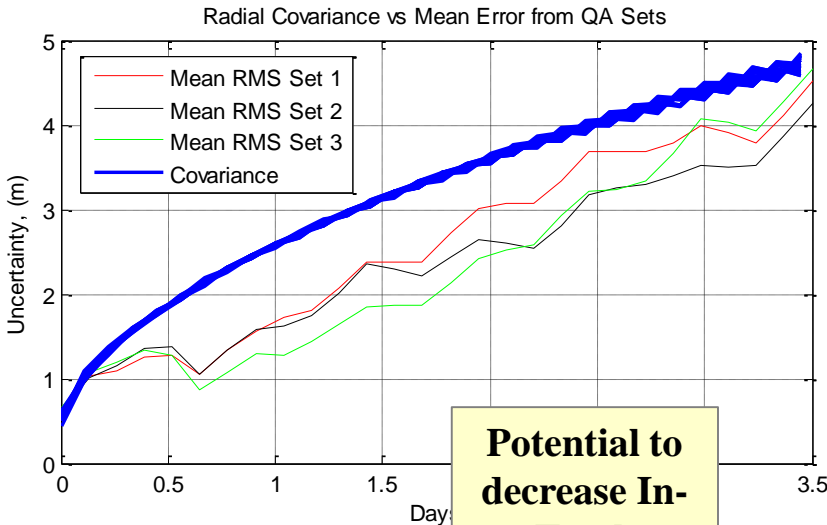


Independent outlier identification results show perfect agreement with outliers identified by automation

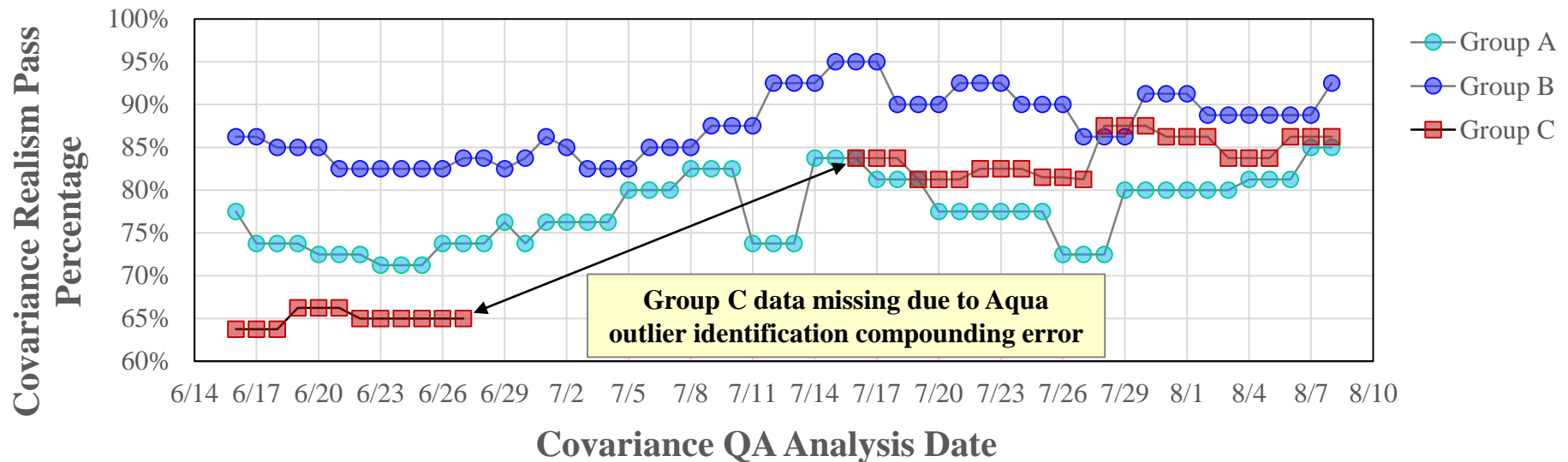
Covariance QA Automation

How to Tune the Covariance

- Once the automated QA of the 3 sets of covariances is finished, the analyst will bring forth the Mean RMS Components Errors for each set to the tuning exercise.
- The component acceleration variances are changed until the Pass Percentages for all three sets of covariances exceed the user specified threshold.
- The analyst will tune the covariance to the **largest Mean RMS Component Error in the Radial and In-Track directions at the final propagation point and to the mid propagation point in the Cross-Track direction** (to achieve the highest level of realism).

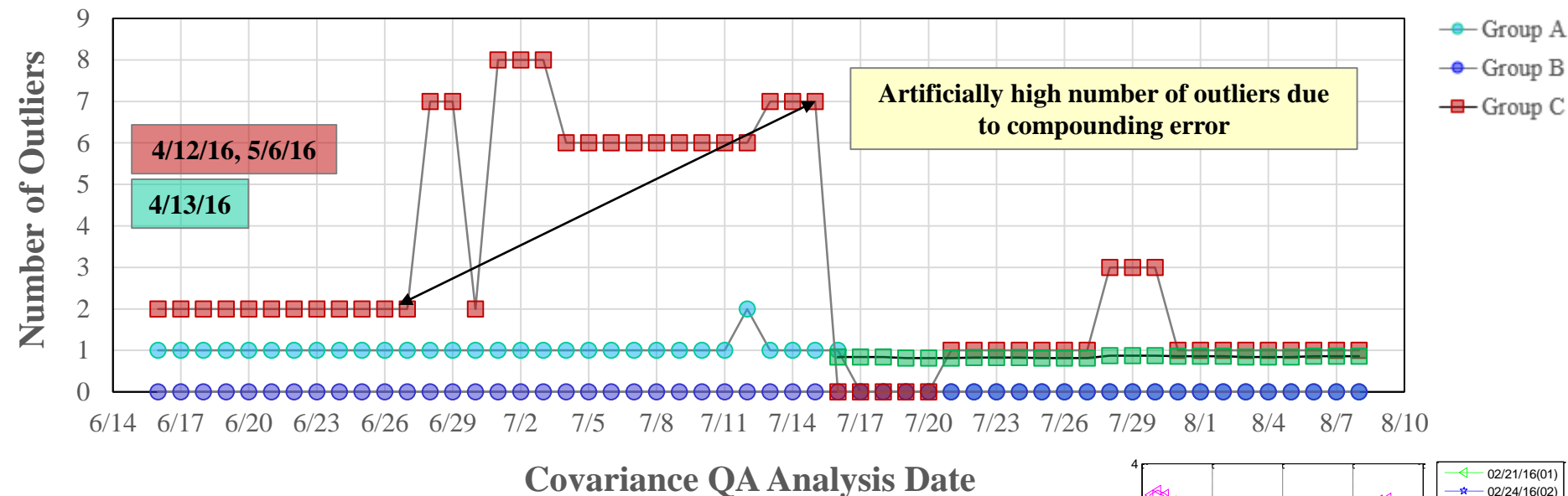


Automated Covariance QA Results to Date (1 of 2)

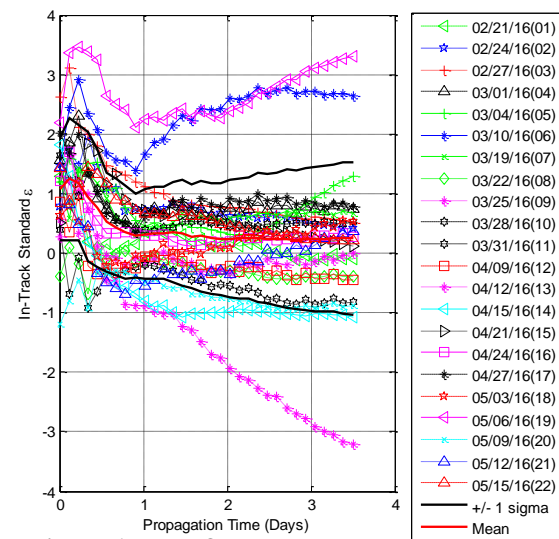


- Aqua Covariance Realism Pass Percentages have been tracked since 16 Jun 2016.
- Each group contains a consistent set of propagations based on the 3-day cadence:
 - Group A always contains propagations beginning on and overlapping the dates 3/14, 3/17, 3/20, etc.
 - Group B always contains propagations beginning on and overlapping the dates 3/15, 3/18, 3/21, etc.
 - Group C always contains propagations beginning on and overlapping the dates 3/16, 3/19, 3/22, etc.
- From 28 Jun to 15 Jul 2016 Aqua incurred an outlier identification compounding error in which more than 4 outliers were being identified that artificially increased the realism pass percentages.
- Group B produces zero outliers, Group A consistently produced at most 2 outliers (4/12, 5/6), and Group C is was impacted by the compounding error but consistently identified 4/13 as an outlier.
- The average Geomagnetic Index (A_p) between 14 Mar 2016 to 3 Aug 2016 was 11 and it rose to 26 ($\sim 2\sigma$) on 13 Apr 2016 and 70 ($>3\sigma$) on 8 May 2016.

Automated Covariance QA Results to Date (2 of 2)



- Group B has not produced any outliers to date.
- Group A has been consistently identifying 13 Apr 2016 as an outlier
- A compounding error in Group C produced up to 8 outliers between 28 Jun and 15 Jun 2016.
 - Specifically, the automated outlier identification test incorrectly runs the Rosner Outlier Test recursively; it identifies 4 outliers from a set, eliminates them, and then reruns the test using the remaining set.
 - The correct usage of the test is to identify up to 4 potential outliers in the set and *only* run the test on those candidates against the entire set.
- Since Group A and B were producing good results, we elected to continue using the software as designed – plans to update the test are imminent.



Overview of Covariance Propagation through Maneuvers

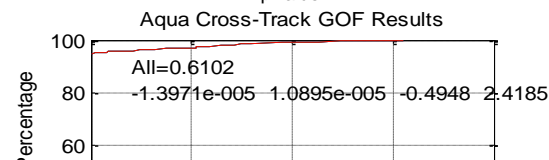
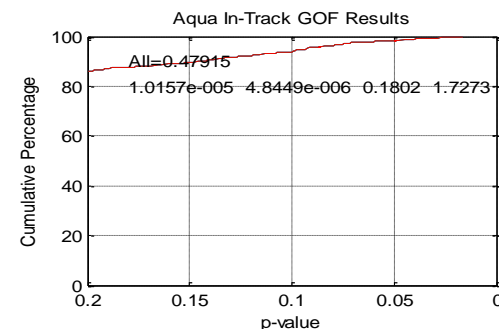
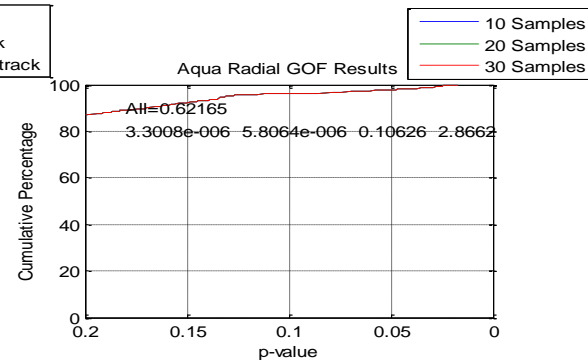
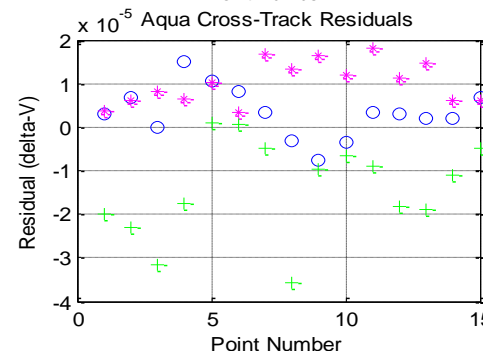
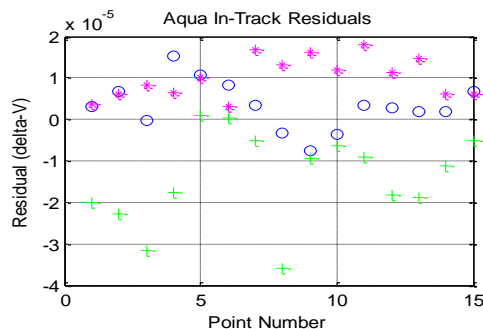
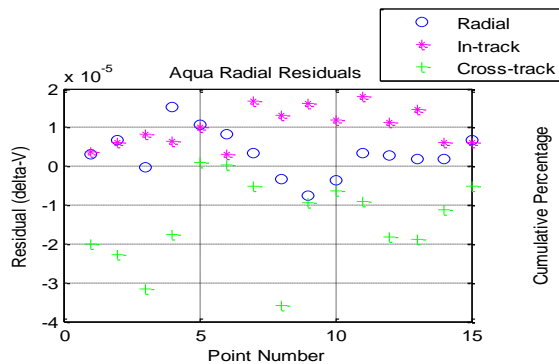
- The EOS FDS team has adopted a method to characterize the maneuver execution errors for the Aqua and Aura spacecraft.
- The motivation of this implementation is to strengthen the validity of the Pc computation.
- The Pc computation uses two major components for two objects in conjunction:
 1. Miss Distance
 2. Predicted Covariances at the TCA
- The miss distance must take into account the state change a maneuver introduces while the covariances must accurately represent the expected errors in the maneuver execution process – **neither is represented by CARA synthesized covariances.**
- The method that EOS FDS has adapted to account for maneuver execution error includes the following stages:
 1. Gaussian distribution testing and outlier investigation of the Delta-V component errors **Operational**
 2. Creation of a Error Covariance Matrix using the preceding Delta-V component errors **Operational**
 3. Error Covariance Matrix Scaling using RIC Scale Factors **Operational**
 4. Application of Dataset Biases (An Enhancement to the Maneuver Planning Process) **Future**
- The preceding method is tested by propagating the Error Covariance Matrix through historical maneuvers and performing a covariance realism analysis on the resulting predicted post-maneuver propagation errors.

Covariance Propagation through Maneuvers

Gaussian Distribution Study of the ΔV Component Errors

Testing for Normality

- Radial, In-Track, and Cross-Track ΔV components for all Aqua and Aura no-slew DMU maneuvers are passed through the Cramer – von Mises EDF test to gauge conformity to a Gaussian distribution
- A resampling investigation is performed in which 1,000 random 10-point samples are chosen and tested.
- A total p-value indicates likelihood of normality for the entire set of 1,000 test results
- The test for normality is segregated into Day/Night maneuvers for Aqua and Over/Under 21 sec for Aura to eliminate potential systematic error and to maintain the current planning strategy.



Validation: Component Errors conform to a Gaussian distribution thus allowing the covariance to represent the error distribution

Mission Operations Working Group

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Covariance Propagation through Maneuvers Implementation

- Linearized Covariance Propagation – The standard formula for linearly propagating a covariance is:

$$P(t_n) = \Phi(t_n, t_{n-1})P(t_{n-1})\Phi^T(t_n, t_{n-1}) + Q(t)$$

where $P(t_n)$ = Initial Covariance Matrix $\Phi(t_n, t_{n-1})$ = State Transition Matrix
 $Q(t)$ = Process Noise Matrix

- The Process Noise Matrix can be broken down further to represent error due to environmental forces and error due to the execution of the maneuver:

$$Q(t) = \Gamma Q_e(t)\Gamma^T + Q_m(t)$$

where $Q_m(t)$ is non-zero only during the execution of the maneuver
 $Q_e(t)$ is a diagonal matrix containing RIC acceleration variances
 Γ = Process Noise Transition Matrix = $\Delta t \begin{bmatrix} \frac{\Delta t}{2} [I]_{3 \times 3} \\ [I]_{3 \times 3} \end{bmatrix}$

Underlying Assumption:

A covariance is the stochastic characterization of the expected errors about the mean state

- If \vec{X} , \vec{Y} , and \vec{Z} are vectors containing Radial, In-Track, and Cross-Track ΔV Component errors of historical maneuvers and \bar{X} , \bar{Y} , and \bar{Z} are the **means of those vectors**, then each column of the Maneuver Execution Error Matrix, $Q_m(t)$, is computed as follows:

$$\frac{1}{N}(\vec{X} - \bar{X}) \times (\vec{Y} - \bar{Y})$$

Covariance Propagation through Maneuvers Covariance Scaling using RIC Scale Factors

- The Maneuver Error Execution Matrix is scaled as follows:

$$P_{ES} = \Lambda P_{\text{error}} \Lambda^{-1} = \begin{bmatrix} \beta_1 & 0 & 0 \\ 0 & \beta_2 & 0 \\ 0 & 0 & \beta_3 \end{bmatrix} P_{\text{error}} \begin{bmatrix} \beta_1 & 0 & 0 \\ 0 & \beta_2 & 0 \\ 0 & 0 & \beta_3 \end{bmatrix}^{-1}$$

Λ = Diagonal Matrix with RIC Scale Factors β_1 , β_2 , and β_3

- Since Λ is diagonal it will scale P_{error} by the square of the appropriate scale factor and the off-diagonal terms by the appropriate combination of scale factors.
- Example of Scaled Maneuver Error Execution Matrix ($\beta_1 = \beta_2 = 1$, $\beta_3 = 3$):

$$P_{\text{error}} = \begin{bmatrix} \mathbf{3.8101E-011} & -1.5669E-011 & 1.8424E-011 \\ -1.5669E-011 & \mathbf{2.4318E-011} & 6.2863E-012 \\ 1.8424E-011 & 6.2863E-012 & \mathbf{1.3024E-010} \end{bmatrix}$$

$$R_{\text{unc}} = 6.1726\text{e-06 km/s}, I_{\text{unc}} = 4.9313\text{e-06 km/s}, C_{\text{unc}} = 1.1411\text{e-05 km/s}$$

$$P_{\text{error scaled}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 3 \end{bmatrix} P_{\text{error}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 3 \end{bmatrix}^{-1} = \begin{bmatrix} \mathbf{3.8101E-011} & -1.5669E-011 & 5.272E-011 \\ -1.5669E-011 & \mathbf{2.4318E-011} & 1.8858E-011 \\ 5.272E-011 & 1.8858E-011 & \mathbf{1.1719E-009} \end{bmatrix}$$

$$R_{\text{unc}} = 6.1726\text{e-06 km/s}, I_{\text{unc}} = 4.9313\text{e-06 km/s}, C_{\text{unc}} = 3.4232\text{e-05 km/s}$$

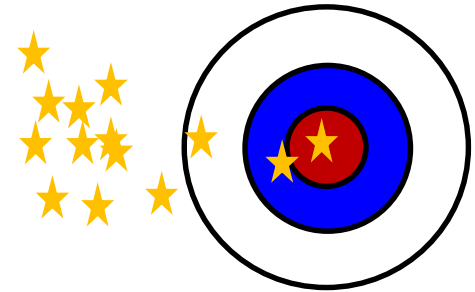
Covariance Propagation through Maneuvers Dataset Biases

- The mean of each of the Radial, In-Track, and Cross-Track ΔV components constitutes the maneuver execution bias, μ .
- If the bias of a certain ΔV component is non-zero and random (systematic errors have been addressed) then the following can be said for that component:
 - The error distribution fluctuates about some positive or negative value instead of being centered at zero
 - The bias is the expected value of the error
 - The satellite is commanded to execute a certain ΔV when the actual expectation of what will be realized is $\Delta V + \mu$

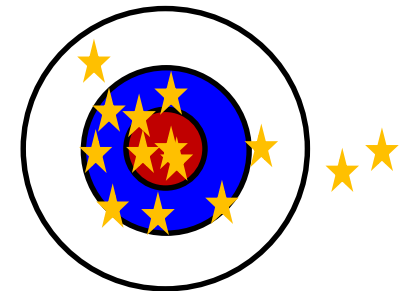
- There are two approaches to make use of bias:

Approach 1 – Add bias to the planned maneuver plan. For example, if an In-Track ΔV component of 10 cm/s is planned and the bias is +2.5 cm/s then this bias is added to the satellite's state estimate propagation at the time of the maneuver.

Approach 2 – Add bias to the commanded maneuver plan. For example, if an In-Track ΔV component of 10 cm/s is planned and the bias is +2.5 cm/s then the plan is changed to 7.5 cm/s prior to the propagation of the satellite's state estimate.



Example of Dataset Bias



Example of Accounting for a Dataset Bias

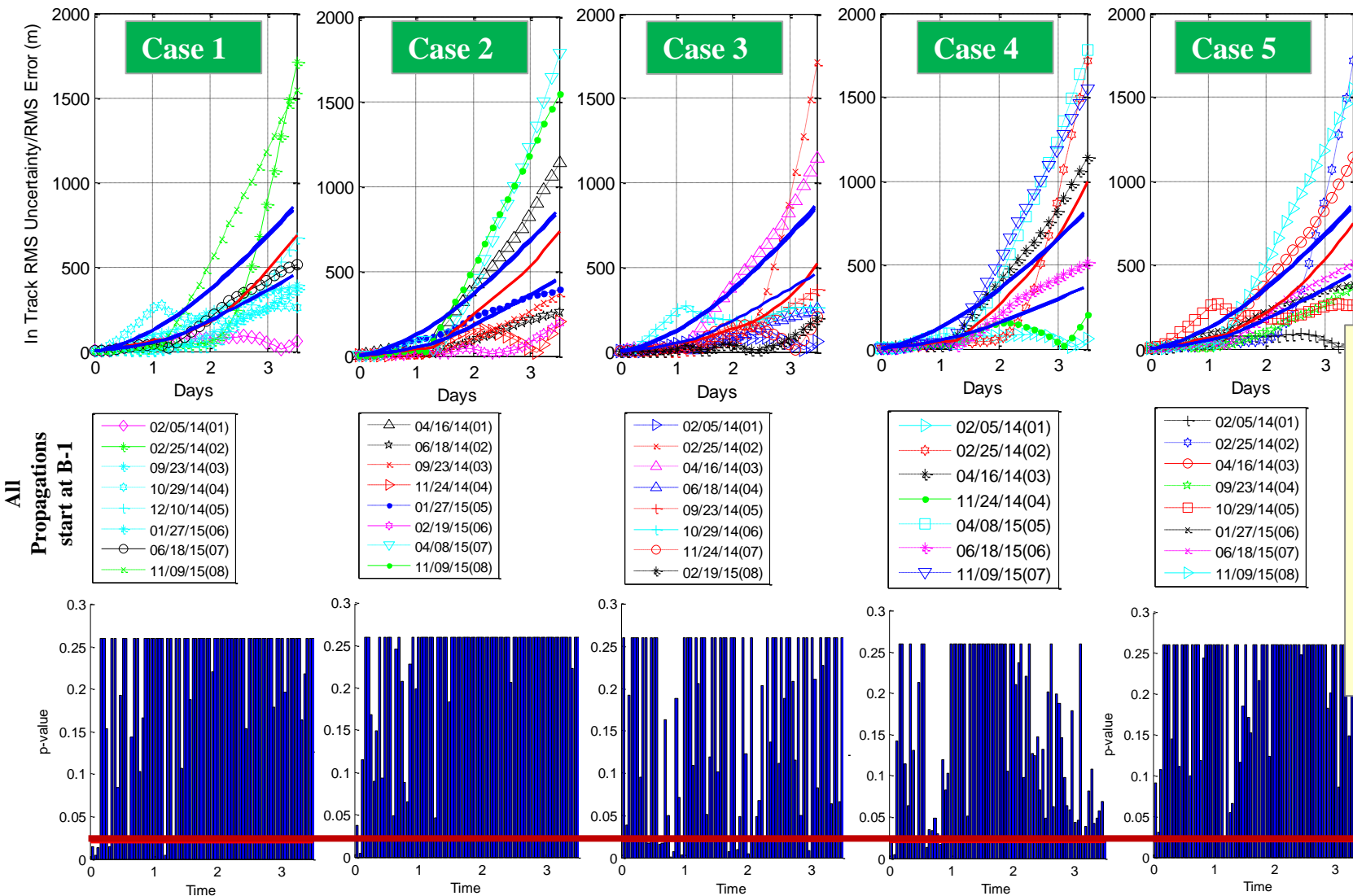
Disclaimer: At this time EOS Maneuver Covariance is not centered around mean component errors (impact described in the next slides)

Covariance Propagation through Maneuvers No-Slew DMU Maneuver Characterization Example

- FDS has access to the following definitive covariances ranging from 2014 to 2016:
 - 29 Aura No Slew DMUs (13 *with burn durations under 21 seconds* and 16 *over 21 seconds*)
 - 24 Aqua No-Slew DMUs (16 *during Orbital Day* and 8 *during Orbital Night*)
- Additionally, there are 15 (8 *under 21*, 7 *over 21*) Aura and 7 (6 *Day*, 1 *Night*) Aqua No Slew DMUs from 2012 to 2013.
- To demonstrate the robustness of the maneuver covariance's representation of maneuver execution errors, FDS performed 5 iterations of selecting 8 random Aura No-Slew DMUs to size the maneuver error covariance matrix, $Q_m(t)$, and propagate it through the remaining 8 No-Slew DMUs—thereby isolating the effects of the 8 remaining No-Slew DMUs on the maneuver error covariance matrix.
- Data from 2012 to 2013 is kept in sizing $Q_m(t)$ (but not used in propagation)
- The 5 test cases are given in the following table (No outliers were identified in normality testing):

Case 1	DMU Used	51	52	53	55	57	58	61	62	65	66	68	74	76	78	79
	DMU Propagated	63	64	71	73	75	77	81	85							
Case 2	DMU Used	51	52	53	55	57	58	61	62	63	64	66	73	75	76	81
	DMU Propagated	65	68	71	74	77	78	79	85							
Case 3	DMU Used	51	52	53	55	57	58	61	62	66	75	76	77	79	81	85
	DMU Propagated	63	64	65	68	71	73	74	78							
Case 4	DMU Used	51	52	53	55	57	58	61	62	66	68	71	73	75	77	78
	DMU Propagated	63	64	65	74	76	79	81	85							
Case 5	DMU Used	51	52	53	55	57	58	61	62	66	68	74	75	76	78	79
	DMU Propagated	63	64	65	71	73	77	81	85							

Covariance Propagation through Maneuvers Maneuver Characterization Goodness-of-Fit Results



Note:
High
Levels of
Covariance
Realism
without
applying
Dataset
Biases

Conclusion

- The EOS FDS team has been using tuned O/O covariance for Aqua and Aura:
 - The automation of the covariance QA has been established, tested, and working as expected.
 - Apart from a well-understood compounding outlier identification error for Aqua, the automation of outlier identification has been established, tested, and working as expected.
- The EOS FDS team has been using O/O covariance with maneuver execution error assuming zero-bias:
 - Gaussian distribution testing of the maneuver component errors has been established and working as expected.
 - Maneuver Execution Error Covariances to be updated on a bi-annual basis.